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Heat Pump Driven by a Gas Engine for Heating and Domestic Hot Water Generation

Amine Mekdache
Ecole des Mines de Paris / Centre efficacité énergétique des systèmes, France/ Engineering Research Innovation for Energy (EREiE), France, amine.mekdache@mines-paristech.fr

Assaad Zoughaib
Ecole des Mines de Paris / Centre efficacité énergétique des systèmes, France, assaad.zoughaib@mines-paristech.fr

Denis Clodic
Engineering Research Innovation for Energy (EREiE), France, denis.clodic@ereie-sas.fr

Heat pump driven by a gas engine for heating and domestic hot water generation

Amine MEKDACHE[1]*, Assaad ZOUGHAIB[2], Denis CLODIC[3]

[1,2]Ecole des Mines de Paris, Center for Energy efficiency of Systems,
5 Rue Léon Blum 91120 Palaiseau, France
amine.mekdache@mines-paristech.fr
assaad.zoughaib@mines-paristech.fr

[1,3]Engineering Research Innovation for Energy,
3 rue de la Croix martre 91120 Palaiseau, France
denis.clodic@ereie-sas.fr

* Corresponding Author

ABSTRACT

Air source heat pumps driven by a gas engine is a known technology. In this paper, we describe a Heat Pump driven by a gas engine that uses grey waters as the cold source producing domestic hot water and heat for the hydronic system. Grey waters are coming exclusively from kitchen's and bathrooms' wastewater and their average temperature is about 30°C. This temperature is constant all along the year. The recovered lukewarm water is stored at atmospheric pressure in a tank. The domestic hot water and the heating water are produced instantaneously by the heat pump and stored in a tank, and hot water is delivered at 58 °C. The paper presents the architecture resulting from a heat integration and exergy analysis study. It allows the heat recovery from the grey waters for the generation of domestic hot water while heat recovery from the engine is used for heating the building. A sensitivity analysis is performed on the ratio between the heat recovered from the grey waters and the heat recovered from the engine when the thermal efficiency of the engine varies. Simulations show also how to handle the engine operation during the heating period and in summer conditions for the climatic conditions of France. The seasonal energy efficiency of the system is calculated based on simulations; they predict a seasonal energy efficiency of 2.1 for generating hot water at 58 °C.

1. INTRODUCTION

Although the energy situation has recently eased with the reduction of oil prices, saving energy is still nationally and internationally needed to meet the goals fixed for tackling the greenhouse gases emissions. One of the main means to reach these goals is energy efficiency.

To reduce energy consumption, standards are reinforced in the building sector because it represents 44% of the energy consumption in France and more than 35% shares of the greenhouse gases emissions.

A low-energy consumption building, as defined in the RT 2012, is a new building that consumes less than 50 kWh/m².yr of primary energy (for heating, hot water, ventilation, lightening and cooling). The greenhouse gases (GHGs) emitted by those buildings are less than 5 kg CO_2.m²/yr. To achieve this level of consumptions, the demand (heat load) is reduced with higher level of insulation but it is important to generate heat with efficient devices such as heat pumps.

Gas engine heat pumps (GHP) differ from a conventional heat pump by the fact that the compressor is driven by a gas engine rather than an electric motor. One of the major differences with electrical driven heat pumps is that part of the heat released by the engine may be recovered and contribute for heating the water. The heat can be collected from both the engine cooling water and the exhaust gas.

The purpose of this study is to design a Heat Pump driven by a gas engine that uses wastewater as the source cold producing domestic hot water and heat for the hydronic system. Wastewater is called grey water because it comes only from the kitchen sink and the bathroom.

2. SYSTEM DESCRIPTION

The basic specifications and schematic diagram of the system are shown in Figure 1.

After being filtered, grey water is stored until the heat pump starts due to a level of domestic hot water (DHW) too low in the storage.

The grey water passes through a first heat exchanger, the pre-heater, to warm up the city water without consuming any energy up to 25 - 29 °C. Then, the grey water, which still at a higher temperature than ambient air, releases energy to the refrigerant of the heat pump that will warm up to 58 °C the city water. The DHW is finally stored until it is used.

The gas engine will transfer its power to the heat pump compressor via a pulley. Thanks to the heat storages, the gas engine will work at a fixed speed and will keep approximatively the same load and can operate at optimum torque and speed. The gas engine burns natural gas inside cylinders, expansion of the gas will push a piston and run the crankshaft which will transmit the rotating motion to the compressor. The gas combustion generates heat at a level which requires cylinder cooling to keep the material at acceptable operating temperatures. A heat transfer fluid (HTF) is flowing inside the engine cooling circuit to release this excess of heat and to keep the engine at an optimal temperature. Exhaust gases released are also at high temperature. About two third of the energy contained in the gas burnt is lost in the cooling loop and the exhaust gases. Those heat losses are recovered by a water circuit and injected in the space heating network of the building during the heating season and used to produce DHW otherwise.

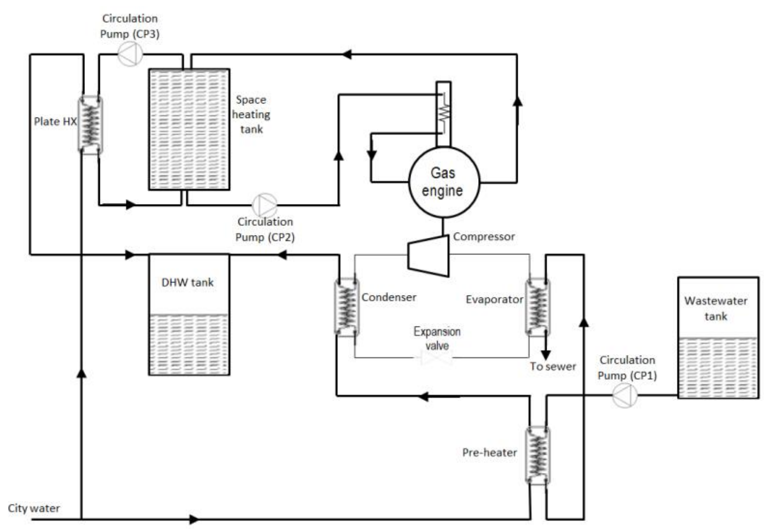

Figure 1: Schematic diagram of the GHP with storage systems

3. MODEL

3.1 Calculation of the heating load and DHW needs

The building simulation is performed using the dynamic building simulation software Pleiades+COMFIE, it allows to define hourly heating and cooling loads to be generated for space temperature control. The selected building to perform this study is a four star hotel. It is an 8 floors building with a total area of around 4,710 m², composed of 147 double-bedded rooms, a business center, a restaurant and an entrance hall.

The location of the building influences the energy consumption of the building. The local climate has to be taken into account, in order to analyse this impact two reference cities are chosen in the North and the south of France: Trappes (North) and Nice (South). The solar radiation is taken into account by the software by an hourly simulation based on statistics made on the last ten years. .

These parameters will fix the boundaries required for the building envelope.

Domestic hot water demand is the other important parameter to define the heating capacity of the heating equipment. The data used to generate DHW withdrawal scenarios come from a domestic hot water guide [AICVF].

The results obtained from these simulations are the following (table 1):

Table 1: Space heating and DHW needs

	Hotel	
	Trappes	**Nice**
Space heating needs (kWh)	87,262	37,955
DHW needs (kWh)	341,230	305,532
Annual DHW consumed (m^3)	6,284	6,284
Space heating needs (kWh/m².yr)	18.5	8.1
DHW needs (kWh/m².yr)	72.4	64.8
Total needs (kWh)	428,492	343,487
Needs (kWh/m².yr)	90.9	72.9

The monthly Space heating and DHW needs calculated by the software are compared in figures 2 and 3.

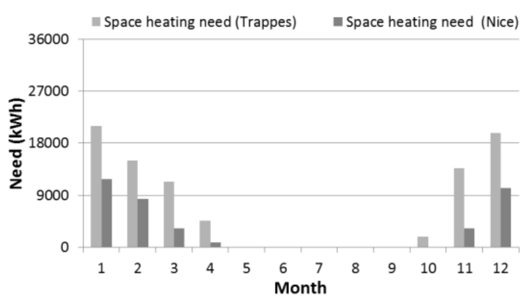

Figure 2: Space heating need

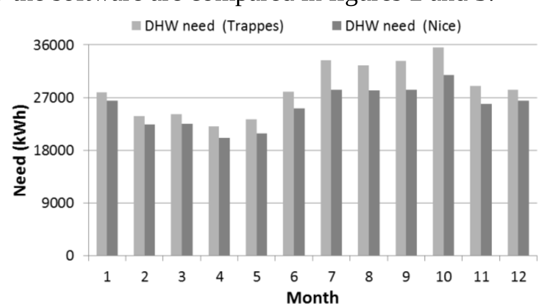

Figure 3: HDW need

As expected, the heating needs in Nice (South) are lower than those of Trappes needs (North).

3.2 Heat pump model

The software Pleiades+COMFIE integrates equipment models. In order to simulate our gas engine driven heat pump behaviour and performance, a separate model is built that uses input data from the building one.

Output hourly data issued by the software are space heating, hot water energy needs and city water temperature.

3.3 Total heating energy

One part of the heating energy is delivered by the heat pump and the other part by the pre-heater. This heat is used to generate DHW. The heat recovery from the engine is used in the space heating network of the building during the heating season and used to co generate DHW otherwise.

Equations (1) to (5) are used in this model to calculate the total heat balance.

$$P_{condenser} = \dot{m}_{DHW} \, . C_p \, (T_{DHW} - T_{cw,o}) \tag{1}$$

$$P_{pre-heater} = \dot{m}_{gw} \, . C_p \, (T_{ww,i} - T_{ww,o}) \tag{2}$$

$$P_{evaporator} = \dot{m}_{gw} \, . C_p \, \left(T_{ww,o} - T_{sewer}\right) \tag{3}$$

$$P_{recovery} = (P_{condenser} - P_{evaporator})\left(\frac{1 - \eta_{engine}}{\eta_{engine}}\right)\eta_{recovery} \tag{4}$$

$$P_{total} = P_{condenser} + P_{pre-heater} + P_{recovery} \tag{5}$$

These equations introduce the engine mechanical efficiency and the heat recovery one. Both efficiencies allow to relate the heat pump operation to the heat recovered from the engine.

3.4 Resources and water flows

Grey water is generated by blending DHW at 58 °C and city water to obtain a blend which is considered at 40 °C. Grey Water is recovered in the wastewater tank. Based on site measurement, 90 % of grey water is recovered, and it gives:

$$\dot{m}_{gw} = 0.9 \, \dot{m}_{DHW} \, \frac{\left(T_{DHW} - T_{cw,i}\right)}{\left(T_{blend} - T_{cw,i}\right)} \tag{6}$$

With the equations (1) to (6), we have:

$$\dot{m}_{DHW} = \frac{P_{compressor}}{C_p \left[\Delta T_{DHW} - 0.9 \, \dfrac{T_{DHW} - T_{cw,i}}{T_{blend} - T_{cw,i}} \, \Delta T_{gw}\right]} \tag{7}$$

With:

$$\Delta T_{DHW} = T_{DHW} - T_{cw,i}$$

$$\Delta T_{gw} = T_{gw,i} - T_{sewer}$$

Figure 4 and 5 show the monthly volume of different water flows.

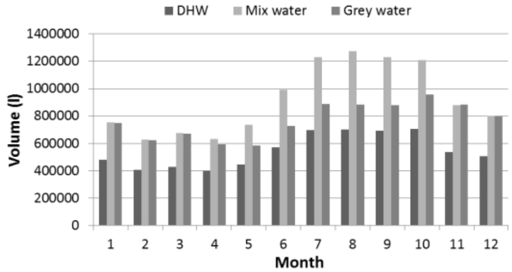

Figure 4: Water flows (Trappes)

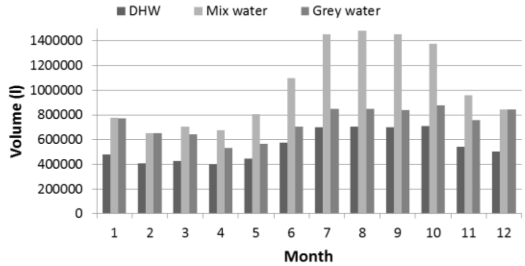

Figure 5: Water flows (Nice)

During the summer, the GPH does not need to use all the grey water as a cold source. Indeed, in the hot season, since there no space heating load, both recovered heat from the engine and the heat pump are used to generate DHW and therefore, the engine operating time is significantly reduced.

3.5 Operating time

Depending on DHW levels and temperature of the space heating storage, the heat pump will start or not. Two main conditions are required to start the hot water production:

- The grey water tank is empty:

As the heat pump draws its energy from grey water, if the storage is empty, the heat pump cannot operate. We can assess the time (in hours) spent to empty the grey water tank:

$$t_{gw-tank} = \frac{\rho \, . V_{gw-tank}}{36 \, . 10^5 \, . \dot{m}_{gw}} \tag{8}$$

- The space heating tank is full:

When the DHW tank is full, the heat pump does not need to produce anymore. To assess this period, we have to make the energy balance that depends on the temperature of the space heating storage. When it reaches its higher limit, heat produced by the engine is transferred to the DHW production. This increases the capacity of DHW production. The time spent to reach the temperature limit of the space heating storage is:

$$t_{SH-tank} = \frac{\left(\frac{\rho \, . C_p \, . V_{SH-tank} \, (T_{SH-limit} - T_{SH-tank})}{36 \, . 10^5}\right) - E_{SH}}{P_{engine} \, (1 - \eta_{engine})} \tag{9}$$

Where E_{SH} is the integral of the space heating load from the actual time until the tank reaches its upper limit.

Within this time, the volume produced of DHW is the following:

$$V_{DHW-SH} = \frac{(P_{pre-heater} + P_{condenser}) \, t_{SH-tank} . 36 \, . 10^5}{\rho \, . Cp \, (T_{DHW} - T_{cw,i})} \tag{10}$$

After that, the engine and the heat pump produce only DHW, time needed to fill the tank is equal to:

$$t_{DHW-SH} = t_{SH-tank} + \frac{\rho \, . C_p (V_{hw-tank} + V_{withdrawal} - V_{DHW,SH})(T_{DHW} - T_{cw,i})}{36 \, . 10^5 \, . (P_{pre-heater} + P_{condenser} + P_{engine} \, (1 - \eta_{engine}) \, \eta_{recovery})} \tag{11}$$

If the temperature limit of the space heating storage is not reached, the time needed to the heat pump to fill the DHW tank is equal to:

$$t_{DHW} = \frac{\rho \, . C_p \left((V_{hw-tank} + V_{withdrawal})(T_{DHW} - T_{cw,i})\right)}{36 \, . 10^5 \, . (P_{pre-heater} + P_{condenser})} \tag{12}$$

The operating time t_{op} is equal to the lowest value between $t_{gw-tank}, t_{DHW-SH}, t_{DHW}$ and 1.

Figure 6 shows the monthly GHP operating time for each building. As said before, the operating time during the warm season is lower than that of cold season.

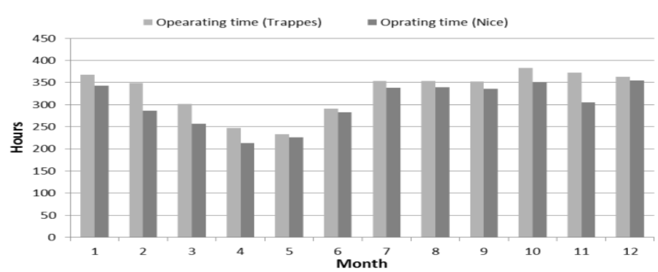

Figure 6: Monthly operating time

3.6 Production and consumption

The table 2 summarizes what the heat pump produces or consumes depending on time conditions.

Table 2: GHP production and consumption

Nature of the flow	Value	Condition
DHW produced (l)	$V_{DHW} = \frac{36.10^5 \left(P_{HP}.t_{SH-tank} + P_{GHP}.(t_{op} - t_{SH-tank})\right)}{\rho.Cp\,(T_{DHW} - T_{cw,i})}$	$t_{SH-tank} < t_{op}$
	$V_{DHW} = \frac{36.10^5.P_{HP}.t_{op}}{\rho.Cp\,(T_{DHW} - T_{cw,i})}$	else
Grey water consumption (l)	$V_{gw-tank} = \frac{36.10^5.\dot{m}_{gw}.t_{op}}{\rho}$	
Space heating storage temperature (°C)	$\Delta T_{SH-tank} = \frac{36.10^5.P_{engine}\left(1-\eta_{engine}\right)t_{SH-tank}}{\rho.Cp.V_{SH-tank}}$	$t_{SH-tank} < t_{op}$
	$\Delta T_{SH-tank} = \frac{36.10^5.P_{engine}\left(1-\eta_{engine}\right)t_{op}}{\rho.Cp.V_{SH-tank}}$	else
Heat pump gas consumption (kWh)	$E_{engine} = P_{engine}.t_{op}$	

3.7 sizing of storage tanks

a) DHW tank:

The DHW tank will store the production of the heat pump to fulfil the withdrawals. DHW level defines when the tank should be filled. Start and stop of the GHP depends on the size of the DHW tank.

The tank size drives the number of operations within a day. The technical constraints impose a continuous operation of the engine and a minimum operation time of 30 minutes. To comply with those constraints, the DHW tank size is set at 1/3rd of the maximal daily water withdrawal volume within a year. Based on the software outputs, this value is:

$$V_{DHW-tank} = {}^{1}/_{3}\ \frac{36.10^5\left(\sum_{i=1}^{24} E_{DHW,i}\right)_{max}}{\rho.Cp\,(T_{DHW} - T_{cw})} \tag{13}$$

b) Space heating tank:

As said before, the engine is equipped with a cooling circuit and energy from the exhaust is also recovered, the size of the hot water tank linked with this circuit (see figure 1) has to be sized

The engine runs at a fixed speed. At nominal operating conditions, the heating losses of the engine represent about 30% of the DHW heating needs. So the volume is given by this equation:

$$V_{SH-tank} = 0.3\ \frac{36.10^5\left(\sum_{i=1}^{24} E_{DHW,i}\right)_{max}}{\rho.Cp\,(T_{CL,o} - T_{CL,i})} \tag{14}$$

c) Grey water tank:

Grey water is collected when the temperature is higher than 25°C. As indicated above, 90% of the energy content if grey water is recoverable.

$$V_{gw-tank} = 0.9\ V_{DHW-tank}\ \frac{(T_{DHW} - T_{cw})}{(T_{mix} - T_{cw})} \tag{15}$$

3.8 Operating conditions

All the parameters of the GHP are now fixed. In order to fulfil the DHW heating needs, when its tank is empty, the heat pump will start. But the GHP by itself cannot satisfy a high instantaneous DHW demand. The solution is to leave a minimal volume of DHW in the tank. This volume has been fixed as 5 % of the highest water withdrawal of the year minus the heat pump production capacity:

$$V_{DHW-tank,limit} = \frac{36\,.\,10^5\;((E_{DHW})_{max} - E_{HP})(1+0.05)}{\rho\,.\,Cp\;(T_{DHW} - T_{cw})} \qquad (16)$$

Figures 7 and 8 show the hourly volume variations in the different tanks:

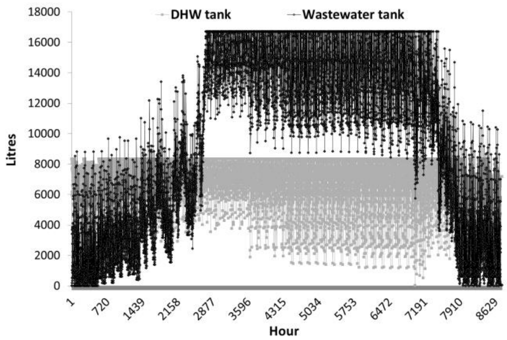

Figure 7: DHW and wastewater tanks (Trappes)

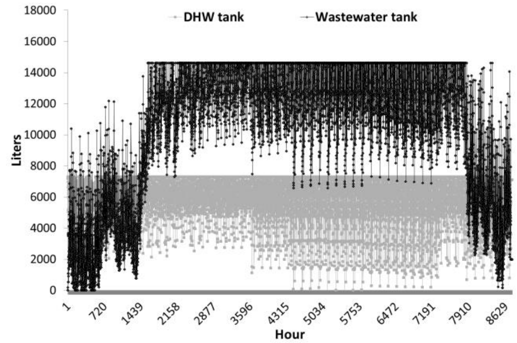

Figure 8: DHW and wastewater tanks (Nice)

Figures allow us to recognize hot season. During this period, GHP does not need to use all available grey water.

4. RESULTS

The results of the simulation using data from the hotel building in the 2 cities are shown in Table 3.

The seasonal GUE of the system is calculated based on simulations; they predict a seasonal GUE higher than 2.2 in both cities.

Space heating production is limited by the recovery of the engine. The high demand in the cold seasons is not fully insured by GHP. This deficit is of the order of 40 % in Trappes and 15 % in Nice.

Figures 9 and 10 show the heating capacity covered by the GHP:

Table 3: results of the simulation

	Hotel	
	Trappes	**Nice**
Gas engine consumption (kWh)	170,449	155,978
RE production (kWh)	223,732	182,428
Space heating covered by the GHP (%)	59%	85%
Gas utility efficiency (GUE)	2.3	2.2
Cpe (kWh/m².yr)	36	33

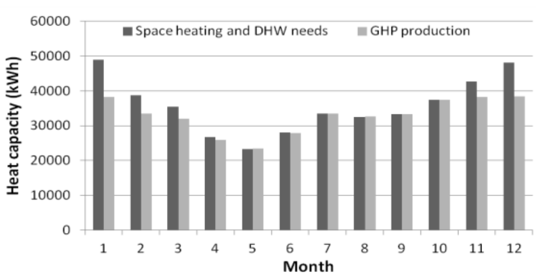

Figure 9: Heats capacity (Trappes)

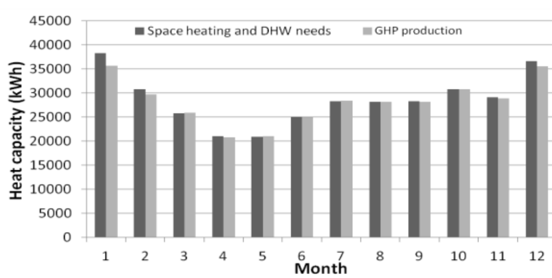

Figure 10: Heats capacity (Nice)

The reduction of space heat needs will allow the GHP to cover it over the year (not only during hot season). This reduction has been fixed by the French regulation (RT 2020).

The energy efficiency (GUP) varies slightly with the season. The overall GUE of the system decreases slightly in hot season due to the low heating load and the high city water temperature. Figures 11 and 12 show the overall energy efficiency variation all over the year.

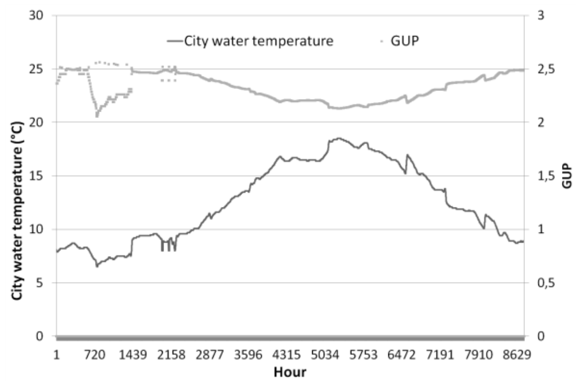

Figure 11: Evolution of the GUE of the GHP and the city water temperature (Trappes)

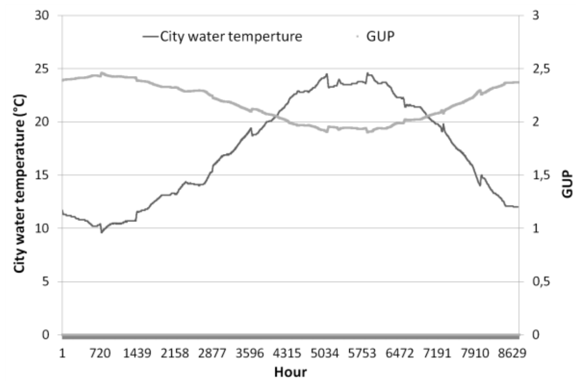

Figure 12: Evolution of the GUE of the GHP and the city water temperature (Nice)

5. CONCLUSIONS AND PERSPECTIVES

The direct heat exchange (recovery) and the thermodynamic lever allow grey water GHP to get high performances. The heat released by the engine, is either valorised in space heating network or in DHW and reduces its operating time. Since the pre-heater keeps almost constant operating conditions of the evaporator and the condenser, the overall efficiency of the system does not vary much within months. This high efficiency puts the grey water GHP as a key equipment for high energy apartment building.

In the future, the reduction of space heat needs will allow the GHP to cover it over the year.

NOMENCLATURE

C_p	Heat capacity	(kJ/kg.K)
E	Energy	(kWh)
$\dot{m}$	Mass flow rate	(kg/s)
op	operating time	(hour)
P	Power	(kW)
T	Temperature	(°C)
t	Time	(hour)
V	Volume	(l)

Greek symbols

η	efficiency	(-)
ρ	density	(kg/m^3)
Δ	Difference	(-)

Subscripts

cl	cooling loop
cw	city water
Cpe	Primary energy consumption
DHW	domestic hot water
GHP	gas heat pump
GUE	gas utility efficiency
gw	grey water
HP	heat pump
hw	hot water
i	inlet
o	outlet
RE	Renewable Energy
SH	space heating

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